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Thresholds of perceivable color difference in silicone: A pilot study

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ABSTRACT

Purpose: The relationship of instrument measured color difference to observer perception of color difference is not currently well-defined in applications related to color for facial prosthetic devices. Determining the threshold of perceivable color difference (ΔE) in silicone will improve the quality of patient treatment and allow for better applications of technology in the production of facial prostheses. The purpose of this study is to determine the threshold of perceivable color difference in silicone and to examine if this threshold varies with light versus dark colors, and/or among three different observer groups.

Material and Methods: Two sets of 40 silicone samples (one simulating light skin and one simulating dark skin) were compared to one standard sample. Sample color was measured using a portable spectrophotometer, and ΔE values between each sample and a standard sample were calculated (Commission Internationale de l'Eclairage CIE (L*a*b*)). Samples were shown to 29 subjects from three groups (12 professionals who work with color, 6 patients with a facial prosthesis, and 11 laypeople) in random order next to a standard sample under controlled viewing conditions. Subjects were asked "Do these samples appear to be the same color?" and responses were analyzed to calculate the ΔE value of the threshold of perceivable color difference in silicone for each subject. Subject thresholds were used to determine average thresholds for each subject group, and for all participants.

Results: No significant difference in the thresholds of perceivable color difference among the three subject groups, or between light and dark sample sets was found. ΔE = 1.025 was calculated as the average threshold of perceivable color difference.

Conclusion: The results of this study indicate that ΔE = 1.0 can be used as a threshold of perceivable color difference in silicone used in facial prosthesis fabrication. Understanding this threshold will be useful in evaluating and integrating technology into the color-matching process of prosthesis production. It can also be used as a clinical standard for color difference comparisons and quality control in prosthetic outcomes. (*Int J Maxillofac Prosthetics 2020;3:12-22*)

INTRODUCTION

Prostheses are an important part of patient rehabilitation physically, psychologically and socially. Patients' satisfaction with their prosthesis is elemental in their ability to cope with their altered body image. Regaining comfort in social situations can also be a major part of prosthetic rehabilitation.[1] Being able to predictably match color is necessary to create aesthetically convincing prostheses and is therefore essential to this rehabilitation (Fig 1).

Color matching is one of the most difficult and important aspects of creating facial prostheses. Traditionally, it has been done by trained anaplastologists adding pigments to silicone in the presence of a patient and matching the color to his or her skin by visual trial and error. This process is problematic because it is time consuming and prone to error due to differences in viewing conditions, and the variability of individual practitioner's skill. Spectrophotometry and computerized color formulation technology have provided clinicians with a more predictable way of coloring silicone. This technology has been shown to produce more predictable color matches with less metamerism than formulations made traditionally, and is therefore a valuable tool.[2] Metamerism is the situation where two colors appear to match in one lighting condition, but no longer appear to match in an alternate lighting condition.[3] Metamerism can be problematic for clinicians in the fabrication of facial prostheses and for the patients who wear them; silicone colors may seem to match the patient's skin well in the clinic, but not under other lighting conditions encountered through the patient's daily activities.

Spectrophotometry is a method of measuring object color using spectral reflectance. Colors can be measured using this technology and described numerically in reference to mathematically defined color spaces. Differences between colors can be calculated and are expressed as ΔE. This technology can be applied clinically to measure a patient's skin color and then create computer-generated color formula that can be used for coloring silicone to match patient's skin for the production of facial prostheses. ΔE has been used as

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a measure of the accuracy of silicone color relative to patient skin and thus can be used in conjunction with iterative color formulation software to successfully generate a silicone color formula that is particular to each patient. [4,5]

There is currently no clinical standard for acceptable color differences (ΔE) in the fabrication of silicone facial prosthesis. The lack of standardization between color assessment equipment and studies makes comparison between equipment and experimental findings difficult; the current state of color matching technology for this particular clinical application is somewhat unclear. Determining a clinical standard for acceptable color differences in silicone used for facial prostheses will contribute to standardizing procedures for color formulation. It will also allow for better comparison among future studies, and ultimately improve applications of color matching technology in the production of facial prostheses. This study was designed to quantitatively determine the average threshold of perception that different groups of subjects have for color differences in silicone as described by ΔE. This will provide a step towards defining the threshold of acceptability and integrating technology into this aspect of prosthesis production. It will also allow for greater consistency in the production of prostheses, and ultimately more accurate color matches between silicone and patient skin. A better understanding of perceivable color difference may also be useful in defining a threshold for color change requiring prosthesis replacement.

The 1976 CIE L*a*b* color space, which can be used to convert measured spectrophotometric spectral data into L*a*b* values, is well known and has been used in similar studies.[4-15] L*, a* and b* describe the dimensions of this color space where L* is lightness, a* represents redness or greenness, and b* represents blueness or yellowness. Color difference (ΔE) can be calculated using these parameters and the formula $\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$ (CIE, 2004).[16] L* values range from 0 (pure black) to 100 (pure white), positive a* values represent a shift toward red, whereas negative a* values represent a shift toward green, and positive and negative b* values represent a shift toward yellow and blue respectively.[10]

Objective color differences can be measured and quantified by devices such as spectrophotometers. Color difference assessments made subjectively vary depending on the physiology of the observer and the viewing conditions. Previous studies (Table 1) by Seelaus and Coward et al.[5] and Paravina et al.[15] have demonstrated correlation between objective, quantitative ΔE values derived via spectrophotometry and subjective appraisals of color accuracy. These studies also highlight the need for standardization across procedures and studies, as comparisons between studies are difficult to make due to differences in methodology, particularly of instrumentation, and the unknown threshold of perceivable color difference for silicone color in the field of prosthetics. Paravina et al.[15] had dental professionals assess pairs of silicone pieces colored to simulate light and dark skin tones and state whether they perceived the two pieces to be the same color. From these data ΔE = 1.2 and ΔE = 2.6 was calculated to be the threshold of perceivable color difference for light and dark samples respectively. The study also had subjects assess whether the paired samples were an acceptable color match, and determined that ΔE = 1.6 for light samples and ΔE = 5.5 for dark samples was the threshold for acceptable color difference. Seelaus and Troppmann[2] have suggested ΔE < 2.0 as a usability tolerance for computerized color formulation, but this suggestion is based on clinical experience as there is no empirically tested clinical standard for silicone facial prosthesis color.

The use of spectrophotometry and iterative computer-generated color formulae has been shown to be effective in producing predictably colored silicone.[4] Silicone colors are created using computer-generated color formulations calculated based on spectrophotometric measurements of subject skin. The silicone's color is then measured and compared to the original skin color measurement and a more accurate, corrected formula is generated. This process continues with improved accuracy as more pigment is added with each iterative formulation. Coward et al.'s[4] study found that there was no significant difference between the ΔE values of the third and fourth iteration of formulae, however the opacity of the fourth iteration may have been too high to make it desirable for use in prostheses. Based on these findings, the researchers recommended that silicone colors mixed using this process go through three iterative formulations during clinical use. However, in the absence of a standardized ΔE tolerance for acceptable color differences, there is no way of proving that three iterations will reach a clinically acceptable level of color accuracy.

Studies of prosthodontic materials (Table 1) have determined visible and acceptable color differences within dental materials. ΔE = 1.0 has been determined to be the limit of color differences between teeth and porcelain detectable to the human eye, and ΔE < 2.75 has been established as a clinically tolerable difference for these materials.[16] Studies have also determined that professionals with experience using dental materials and color matching are more discriminating than subjects with no experience or knowledge of these materials.[8] A study of color differences in composite restoration pieces compared to patient tissues determined that different subject groups found varying amounts of color difference to be acceptable. Acceptable ΔE values were determined to be 2.18 by dentists, 1.78 by dental auxiliaries, 2.69 by

Table 1. Summary of ΔE thresholds in other studies.

Study	ΔE findings
Paravina et al. [15]	ΔE = 1.2(light silicone) and ΔE = 2.6 (dark silicone) for perceivable color difference. ΔE = 1.6 (light silicone) and ΔE = 5.5 (dark silicone) for acceptable color difference.
Ragain and Johnston.[8]	ΔE = 2.29 as limit of acceptable difference between composite tooth restoration material and teeth.
Leow et al.[10]	ΔE = 0.8 (light silicone) and ΔE = 1.3 (dark silicone) for perceivable color difference. ΔE = 1.8 (light silicone) and ΔE = 2.6 (dark silicone) for acceptable color difference.
Seelaus and Troppman.[2]	ΔE = 2 as arbitrary usability tolerance for computer generated silicone color formulations.
Wee et al.[17]	ΔE = 1 as limit of perceivable difference between porcelain and teeth.

patients, and 2.52 by scientists, for an average of 2.29 for all subjects tested.[8]

A study of hand prostheses has determined that the perceivable color difference varies with the lightness of the color. The study found the thresholds for perceptible and acceptable color difference to be ΔE = 0.8 and ΔE = 1.8 for fair-shade prostheses, and ΔE = 1.3 and ΔE = 2.6 for dark-shade prostheses respectively.[10] This study was performed using a series of silicone fingers with slightly different base colors relative to a silicone hand. While still useful in establishing the tolerance of the human eye to color differences, factors such as the shape of the samples and glazes applied to simulate the nature of an actual prosthesis complicate the results of this study.

Based on Leow et al.[10] and Paravina et al.[15], clinical tolerance for color difference appears to be greater for dark skin than light skin. This suggests that there could be a need for different standards based on the lightness of the skin color. It is suggested that tolerance for a higher ΔE value in darker skin is due to lower reflectance from darker, more concentrated pigments.[10] Wee et al.[11] explored a method for grouping skin colors with similar L*a*b* values through cluster analysis resulting in the creation of five skin color clusters. Based on these findings it may be possible that ΔE tolerances vary among color clusters.

Many aspects of a prosthesis' success are evaluated using ΔE as a measure of performance or accuracy. Material attributes, such as color stability during aging[6,12] rely on ΔE measurements to evaluate material integrity and performance. Relative accuracy of different types of spectrophotometers is also determined using ΔE values.[13] Determining the threshold of color difference perception in silicone will help determine if results from studies like this have any clinical significance. It can also be applied to clinical practice as a tool for predicting and deciding when to replace prostheses due to discoloration. Prosthesis-skin color matches can also be measured as a means of quality control.

The purpose of this study was to determine the threshold of perceivable color difference in silicone and to establish whether or not this threshold varied with light and dark colors. Additionally, this study examined whether thresholds of perception differ among different observer types. Previous studies have examined subject groups of either dental professionals[15] or lay people[10] but not different groups of observers assessing the same sample set. The information on thresholds of perceivable color difference in silicone from this study will be useful in setting an acceptable difference in facial prosthesis color relative to patients' skin, and in establishing a standard ΔE value that can be applied across future research and in clinical practice. It will be useful in interpreting the clinical significance of other studies relating to the color properties of facial prosthetic materials, and help to define standards relating to novel applications of color matching technology in this field.

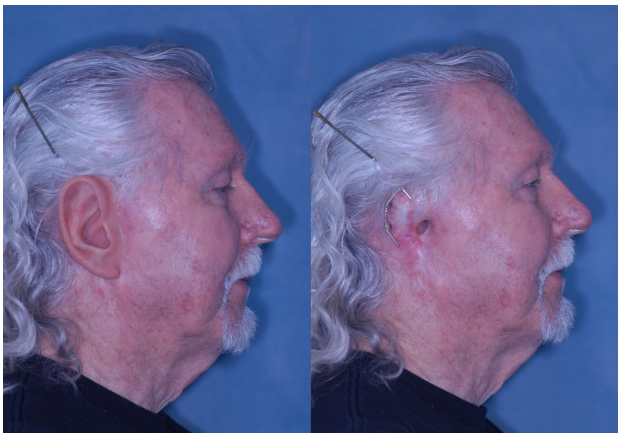

Fig 1. Patient with and without right auricular prosthesis.

MATERIALS AND METHODS

Sample Preparation

A-2186F RTV addition-cure silicone and intrinsic pigments (Factor II, Inc., Lakeside, AZ) were used to create silicone samples. Samples were catalyzed

per manufacturer instructions and cured in 1" square dental stone molds for 45 minutes at 80˚C. Samples were prepared with a matte surface. Sample thickness and opacity prevented any effects of the background color on perceived or measured sample color. Two sets of 40 square samples (25mm x 25mm x 7mm) were made (Fig 2). Pigments were added to silicone to create a homogenous base color. The standard sample and control samples were made from this mix of silicone without additional pigments. Other samples were created by adding varying amounts of pigment to the base color by eye. Each sample set consisted of a standard sample, three control samples, and 37 other samples of varying color (Tables 2 and 3). One set of lighter (L*≈69) and one set of darker (L*≈45) silicone samples were included for comparison. Compared to the control, samples ranged from Δa^* = -0.79 to Δa^* = 3.08 for light samples and Δa^* =-3.61 to Δa^* = 1.49 for dark samples, and from Δb^* = -1.71 to Δb^* = 3.01 for light samples and Δb^* = -1.57 to Δb^* = 2.61 for dark samples.

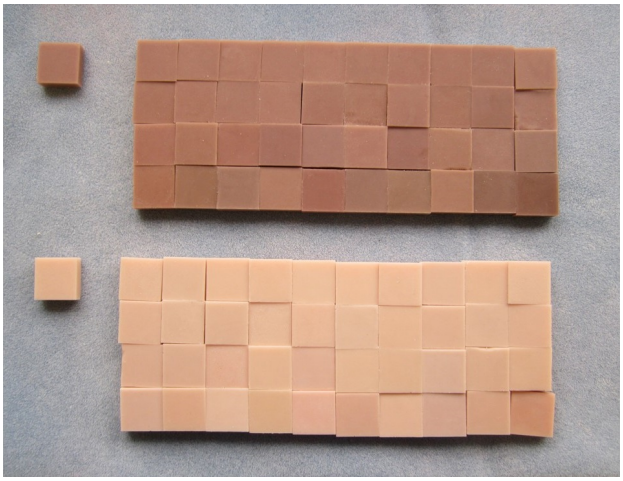

Fig 2. Dark and light sample sets. Each set contained one standard, three controls and 37 other samples.

Instrumentation

Spectrophotometric measurements were made using a CM-700d/600d portable spectrophotometer (Konica Minolta Optics Inc., Ramsey, NJ) with D65 illuminant, diffuse illumination, and 8 degree viewing angle. The spectrophotometer was calibrated per manufacturer specifications. Five measurements were made and averaged to calculate L*, a* and b* values for each sample. Color difference between each sample and the standard was calculated as a ΔE value using the formula $\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$ based on values for L*, a* and b* recorded by the spectrophotometer. Measurements and calculations were made based on Commission Internationale de l'Eclairage CIE (L*a*b*) parameters.[16]

Subject Evaluation of Samples

Recruitment of subjects was approved by University of Illinois Office for the Protection of Research Subjects, Research Protocol # 2012-093. Subjects were recruited at the UIC Craniofacial Center via email and in person.

Three subject groups were tested: professionals who work with color, patients who have a silicone prosthesis, and laypeople. All subjects were 18 years of age or older and passed an Ishihara color test demonstrating that they were not colorblind.[18]

Samples were presented to subjects in a Macbeth Judge II-S Viewing Booth (Gretag Macbeth, New Windsor, NY). The viewing area measured 22.25 inches high by 27 inches wide by 22.25 inches deep, and had low gloss, neutral gray (Munsell N7) colored walls and floor. Samples were viewed under standard D65 lighting provided by two 6500K/D65 bulbs (model F20T12/65GretagMacbeth, New Windsor, NY). Care was taken to ensure that subjects viewed the samples at a 45-degree angle to the sample (Fig 3).

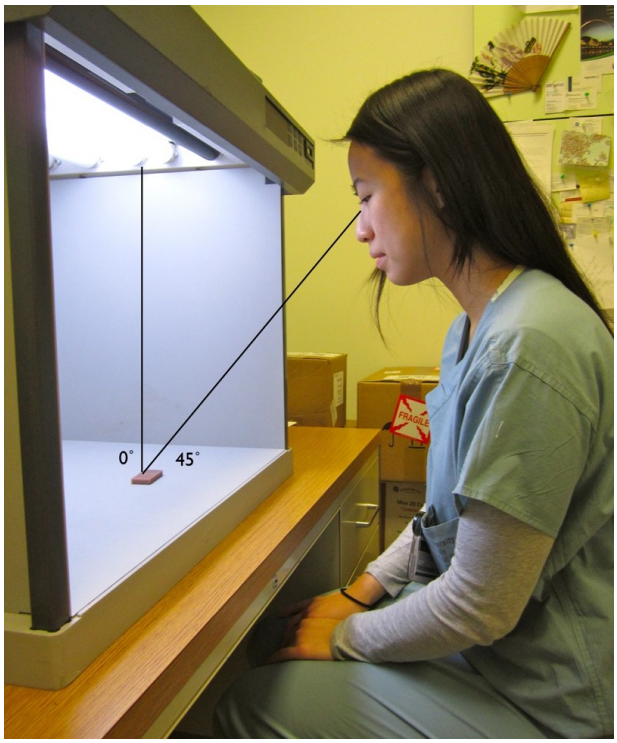

Fig 3. Color viewing booth and subject observing samples.

Pairs of samples were placed before the subject in random order. Samples were positioned adjacent to one another in direct proximity. The position of the standard sample (right or left) was assigned at random. Each pair of samples contained the standard for that set and one other sample from that set (Fig 4).

Table 2. Light sample set CIELAB measurements and ΔE calculations.

Sample	L*	a*	b*	ΔL*	Δa*	Δb*	ΔEab*
L1 (control)	69.50	5.65	12.08	0.19	-0.08	-0.20	**0.29**
L2 (control)	68.99	5.47	12.00	-0.33	-0.26	-0.28	**0.50**
L3 (control)	69.19	6.04	12.66	-0.12	0.31	0.38	**0.51**
L4	68.87	5.93	12.55	-0.45	0.20	0.27	**0.56**
L5	69.57	5.55	12.76	0.25	-0.18	0.48	**0.57**
L6	68.77	5.84	12.57	-0.55	0.11	0.29	**0.63**
L7	69.60	6.34	12.50	0.29	0.61	0.22	**0.71**
L8	69.20	6.44	12.40	-0.12	0.71	0.12	**0.73**
L9	68.82	6.16	12.65	-0.49	0.43	0.37	**0.75**
L10	69.82	5.70	11.69	0.51	-0.03	-0.59	**0.78**
L11	69.32	6.46	12.63	0.01	0.73	0.35	**0.81**
L12	69.02	5.17	11.76	-0.30	-0.56	-0.52	**0.82**
L13	68.52	5.62	12.10	-0.79	-0.11	-0.18	**0.82**
L14	70.07	5.54	11.85	0.75	-0.19	-0.43	**0.89**
L15	69.43	6.54	11.85	0.11	0.79	-0.43	**0.91**
L16	69.47	4.94	11.55	0.16	-0.79	-0.73	**1.09**
L17	69.43	6.25	13.38	0.12	0.52	1.11	**1.23**
L18	68.34	6.55	12.43	-0.98	0.82	0.15	**1.28**
L19	69.91	6.58	13.03	0.60	0.85	0.75	**1.28**
L20	68.38	6.65	12.48	-0.93	0.92	0.20	**1.32**
L21	69.95	7.01	13.11	0.64	1.28	0.83	**1.65**
L22	69.65	6.92	13.39	0.33	1.19	1.11	**1.66**
L23	68.69	7.26	12.04	-0.63	1.53	-0.24	**1.67**
L24	69.79	5.65	13.89	0.47	-0.08	1.61	**1.68**
L25	70.06	5.63	13.84	0.75	-0.10	1.56	**1.73**
L26	69.45	7.56	12.37	0.14	1.83	0.09	**1.83**
L27	68.83	5.58	14.19	-0.49	-0.15	1.19	**1.98**
L28	71.24	6.35	12.90	1.92	0.62	0.62	**2.11**
L29	68.95	6.59	14.17	-0.36	0.86	1.89	**2.11**
L30	68.79	6.43	14.51	-0.52	0.70	2.23	**2.40**
L31	71.64	6.51	12.37	2.32	0.78	0.09	**2.45**
L32	69.25	6.89	14.72	-0.07	1.16	2.44	**2.70**
L33	72.31	5.99	12.58	3.00	0.26	0.30	**3.02**
L34	68.94	5.43	15.29	0.38	0.30	3.01	**3.04**
L35	69.53	8.81	12.60	0.21	3.08	0.32	**3.10**
L36	66.76	7.79	13.44	-2.56	2.06	1.16	**3.48**
L37	70.91	8.02	14.71	1.59	2.29	2.43	**3.70**
L38	65.76	6.10	10.57	-3.55	0.37	-1.71	**3.96**
L39	65.58	7.08	13.14	-3.74	1.35	0.86	**4.07**
L40	65.63	8.35	13.24	-3.68	2.62	0.96	**4.63**
L Standard	**69.32**	**5.73**	**12.28**				

Table 3. Dark sample set CIELAB measurements and ΔE calculations.

Sample	L*	a*	b*	ΔL*	Δa*	Δb*	ΔEab*
D1 (control)	44.91	7.74	10.75	-0.02	0.00	0.06	**0.06**
D2 (control)	44.83	7.72	10.69	-0.10	-0.02	0.00	**0.10**
D3 (control)	44.77	7.69	10.97	-0.23	-0.05	0.27	**0.36**
D4	44.56	7.72	10.72	-0.37	-0.01	0.02	**0.37**
D5	45.21	7.99	10.99	0.28	0.25	0.30	**0.48**
D6	45.19	7.54	11.13	0.26	-0.19	0.44	**0.54**
D7	45.46	7.90	10.80	0.53	0.17	0.11	**0.56**
D8	45.15	8.07	11.19	0.22	0.33	0.49	**0.63**
D9	45.10	7.22	10.28	0.17	-0.51	-0.42	**0.68**
D10	44.75	8.06	11.27	-0.18	0.33	0.57	**0.68**
D11	44.31	7.77	11.03	-0.63	0.04	0.34	**0.71**
D12	44.37	7.95	11.29	-0.56	0.21	0.59	**0.84**
D13	44.82	7.19	10.03	-0.11	-0.54	-0.67	**0.87**
D14	45.81	7.58	10.57	0.88	-0.16	-0.13	**0.91**
D15	43.95	7.54	10.50	-0.98	-0.19	0.20	**1.02**
D16	45.46	7.19	11.42	0.53	-0.53	0.73	**1.05**
D17	43.86	7.77	10.42	-1.07	0.04	-0.28	**1.11**
D18	44.18	7.41	11.77	-0.75	-0.32	1.07	**1.34**
D19	43.64	8.10	10.88	-1.29	0.36	0.19	**1.35**
D20	43.60	7.50	10.38	-1.33	-0.24	-0.32	**1.39**
D21	44.56	9.03	11.31	-0.37	1.29	0.62	**1.48**
D22	45.67	7.60	12.04	0.74	-0.13	1.34	**1.54**
D23	44.42	9.23	11.08	-0.51	1.49	0.38	**1.62**
D24	43.77	8.36	9.58	-1.16	0.62	-1.11	**1.72**
D25	45.96	7.89	9.26	1.04	0.10	-0.43	**1.78**
D26	46.96	7.93	10.39	2.03	0.20	-0.31	**2.06**
D27	43.20	8.40	9.76	-1.73	0.66	-0.94	**2.08**
D28	46.49	7.16	11.98	1.56	-0.58	1.29	**2.10**
D29	47.25	7.18	10.26	2.32	-0.55	-0.44	**2.42**
D30	46.91	6.30	10.83	1.98	-1.43	0.13	**2.45**
D31	45.20	8.59	13.30	0.27	0.85	2.61	**2.76**
D32	43.42	5.44	11.97	-1.51	-2.30	1.28	**3.03**
D33	43.60	4.59	10.11	-1.33	-3.14	-0.59	**3.46**
D34	47.96	7.87	12.53	3.03	0.13	1.83	**3.54**
D35	41.39	8.76	10.36	-3.54	1.02	-0.33	**3.70**
D36	42.73	4.85	9.12	-2.20	-2.89	-1.57	**3.96**
D37	43.23	4.12	11.44	-1.70	-3.61	0.75	**4.06**
D38	48.22	7.66	13.28	3.29	-0.08	2.58	**4.18**
D39	40.30	5.27	9.60	-4.63	-2.47	-1.10	**5.36**
D40	38.94	7.34	10.89	-5.99	-0.40	0.19	**6.01**
D Standard	**44.93**	**7.74**	**10.70**				

Subjects were asked “Do these samples appear to be the same color?” Subject responses were recorded in a binary scoring system where 0 represented the subject perceiving the samples as the same color and 1 represented the subject perceiving the samples to be different colors.

Statistical Analysis

For the purposes of this study, the threshold of perceivable color difference was defined as the ΔE value at which the probability of a subject (observer) perceiving color difference was 50%.[8,15] The threshold of perceivable color difference for both the light and dark silicone samples were calculated for each subject. For each subject and viewing condition (light or dark) logistic regression was used to generate an equation to predict the probability of that subject perceiving a color difference at a given ΔE, and a line of best fit was drawn to illustrate this equation (Fig 5). The ΔE value with 50% probability of that subject perceiving a difference was calculated for both light and dark samples. A similar method was used by Ragain and Johnston[8] and Paravina et al.[15] to calculate thresholds of observer perceptibility. Mean thresholds of perception were calculated for each subject group, and across all subjects as was standard deviation and median. An independent groups t-test was used to compare between the thresholds of perception calculated for light and dark sample sets. Both light and dark threshold data for the patient group showed signs of not being normally distributed (kurtosis = 2.8 and 4.8 respectively) so a non-parametric Kruskal Wallis test was used to compare perception thresholds between the professional, patient and layperson subject groups.

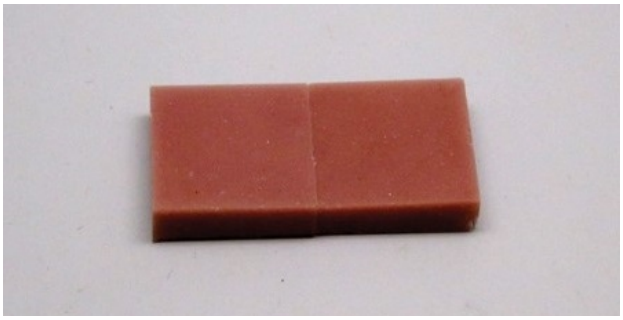

Fig 4. Presentation of silicone samples to subjects.

RESULTS

The mean (SD), median, minimum and maximum thresholds of perception from all subjects and for each subject group are shown in Table 4. The mean (SD) of thresholds for the lighter sample set was found to be ΔE=1.02 (0.35) ranging from ΔE=0.38 to ΔE=1.79 with a median of ΔE=1.04. For the darker set the mean (SD) threshold of perception for all subjects was found to be ΔE=1.03 (0.38), ranging from ΔE=0.16 to ΔE=1.80 with a median of ΔE=1.02 (Table 4, Fig 6). For the lighter color set of samples the thresholds of perception were found to have mean (standard deviation) and median values of ΔE =0.96 (0.30) and ΔE=0.88 for the professional group, ΔE=1.00 (0.22) and ΔE=1.03 for the patient group, and ΔE=1.10 (0.46) and ΔE=1.04 for the layperson group (Fig 7). When observing the darker sample set the mean (SD) and median threshold of perception were found to be ΔE=0.92 (0.22) and ΔE=0.97 for the professional group, ΔE=1.26 (0.40) and ΔE=1.35 for the patient group, and ΔE=1.01(0.49) and ΔE=1.15 for the layperson group (Fig 7). An independent t-test showed that the difference between mean thresholds of perception for light and dark sample sets was not significant, (t = -0.101 df = 58, p = 0.920 two-tailed). A Kruskal Wallis test shows no significant difference between thresholds of perception across all three subject groups for either light or dark sample sets (light: χ^2 (2, N=29) = 0.39, p=0.82, dark: χ^2 (2, N=29) = 5.73, p=0.06).

DISCUSSION

As shown in the Table 4 the mean threshold of perceivable color difference was ΔE = 1.02 for the lighter sample set and ΔE = 1.03 for darker sample set. This is in keeping with previous studies[10,14,17] involving silicone and prosthetic dentistry materials that found ΔE of approximately 1.0 to be the threshold of color difference perceivable to subjects. Thresholds of perceptibility were lower than both light (ΔE = 1.2) and dark (ΔE = 2.6) perceptibility thresholds calculated by Paravina et al.[15]

Professionals who work with color were expected to have a greater ability to perceive color differences in this study, as had been observed in previous studies involving dental materials.[8] The threshold of perceivable color difference for this group was expected to have a lower ΔE value than other subject groups. Findings suggest similarity to this expectation and to previous findings by Ragain and Johnston[8] as the professional group had the lowest threshold for both light and dark sample sets, however analysis did not find the difference between thresholds of perceptions of the subject groups to be significant.

Previous studies have found that the threshold of perceivable color difference is higher in darker silicone samples.[10,15] This study did not find significant difference between subject thresholds of perception in light and dark sample sets. The mean thresholds for both sets of samples were found to be almost identical (ΔE = 1.02 for the lighter set, ΔE = 1.03 for the darker set) (Table 4). It should be noted that these thresholds are very similar to those found by Leow et al.[10] where thresholds of perceivable color difference were calculated to be ΔE = 0.8 for lighter samples and ΔE = 1.3 for darker samples.

Table 4. Summary of group ΔE thresholds of color difference perception in light and dark sample sets.

Sample set		Subject group perception threshold			
		Professional ΔE	Patient ΔE	Layperson ΔE	All Subjects ΔE
Light	Mean	0.96	1.00	1.10	1.02
	Median	0.88	1.03	1.04	1.04
	Standard Deviation	0.30	0.22	0.46	0.35
	Minimum	0.51	0.58	0.38	0.38
	Maximum	1.49	1.22	1.79	1.79
Dark	Mean	0.92	1.26	1.01	1.03
	Median	0.97	1.35	1.15	1.02
	Standard Deviation	0.22	0.40	0.49	0.38
	Minimum	0.61	0.16	0.48	0.16
	Maximum	1.28	1.80	1.57	1.80

Average L* values for both the lighter (L*= 69) and darker (L*= 45) sample sets in this study were very similar to the average L* values in Paravina et al.[15] (L*= 69.7 for the lighter set and L*= 48.7 for the darker set), however both were lighter than those in Leow et al.[10] (L* = 55.3 for the lighter set, L* = 37.22 for the darker set). These differences in the average L* values of lighter and darker sample sets among these three studies does not point to strong correlation between L* value and perceptibility threshold as both sample sets in Leow et al.[10] demonstrate similar ΔE values to the lighter sample set in this study but lower ΔE values than in Paravina et al.[15] where sample sets had higher average L* values. Further study with a larger sample size, particularly in the patient group will bring a higher level of confidence to the analysis.

It is important to keep in mind that many factors influence the perception of color. While environmental factors such as illumination and angle of observation were standardized for this experiment, many factors like the physiological conditions of each subject could not be controlled. With this in mind, a reasonable assessment of perceivable color differences useful for clinical applications of silicone color matching is ΔE = 1.0 based on data collected in this study. Some studies have found that thresholds of perceivable and acceptable color difference are the same,[14] while others have suggested that the threshold of acceptability is higher than the threshold of perceptibility.[10,15] While more information is needed to definitively determine if a higher threshold would be acceptable for clinical color matches in the production of facial prostheses, a prudent course of action would be to apply the threshold of perceivable color difference of ΔE = 1.0 as a clinical standard for acceptability until further clarification is achieved. Methods of grouping colors into clusters based on similar L*a*b* values[11] could be useful in further determining what color differences are clinically significant for different skin colors. The researchers acknowledge that an improved understanding can be achieved by also examining color difference using the DeltaE00 formulae.[19]

Examination of perceivable color differences under different lighting conditions or in other commonly used silicones will help further clarify where an average threshold of perception lies as our study tested only A-2186F silicone under D65 illumination. Given the current study's small sample size, a larger study with more subjects and more samples will also provide a more complete indication of where this threshold lies. A larger number of subjects, especially in the patient subject group, would allow for more meaningful statistical analysis.

It should be noted that the color of silicone prepared in this manner is non-homogenous. Multiple spectrophotometric readings from the same sample consistently yield slightly different measurements (ΔE's of approximately 0.1 were observed between measurements of the same sample). ΔE values calculated for this study are averages, which is expected in the instrumentation used and well within the tolerances of measurement for this study.

Minor differences in surface texture, the presence of small air bubbles and small height discrepancies

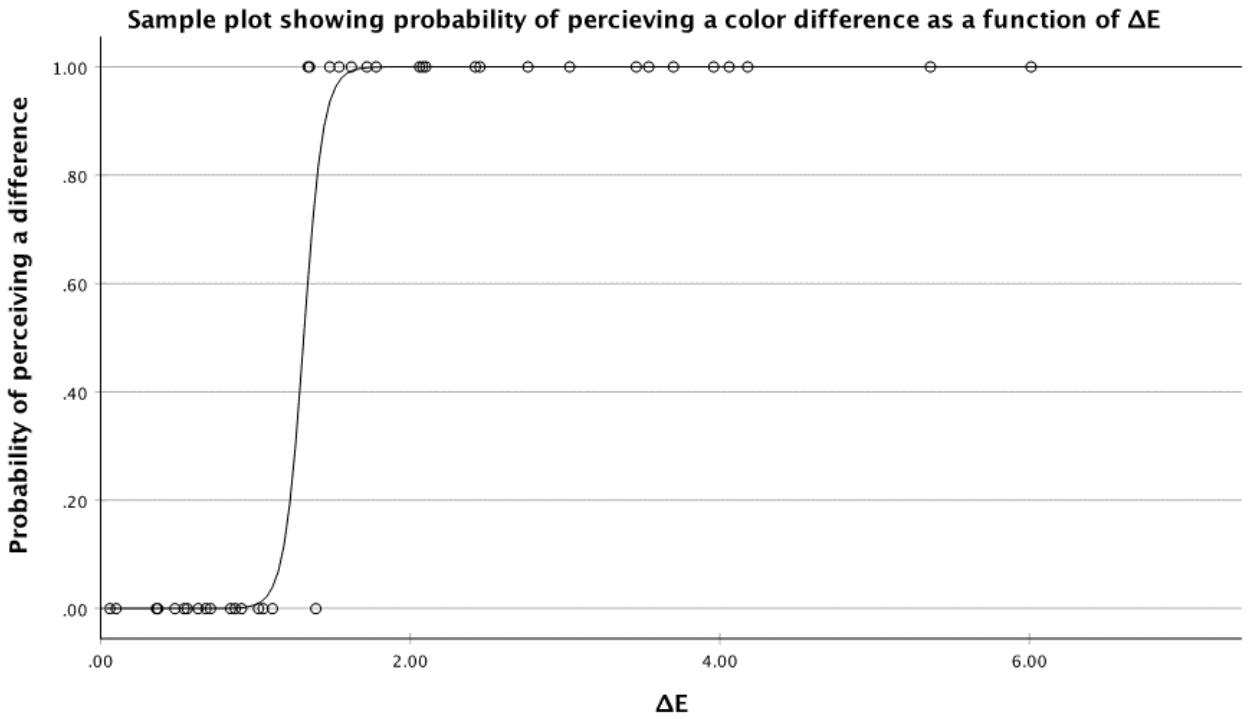

Fig 5. Example plot showing the probability of one subject perceiving a color difference between samples as a function of ΔE. The reference line represents the equation generated using logistic regression used to calculate the 50% probability of perceiving a color difference as ΔE= 1.312 for this subject observing the dark data set.

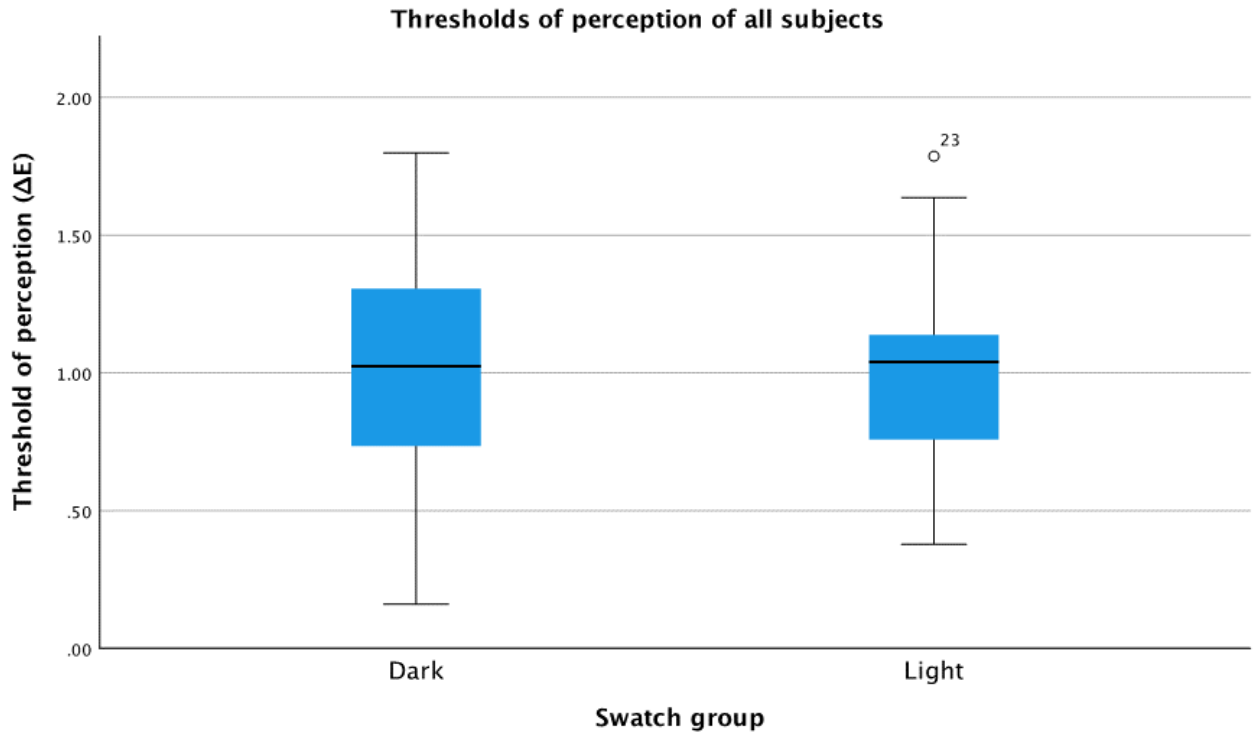

Fig 6. Boxplot depicting the distribution of perception thresholds of all test subjects for dark and light samples sets.

between some samples and the standard could also have affected the perception of color differences in some cases. Some subjects commented on these differences, stating that it made it more difficult to assess the actual color of samples; and all subject groups were represented in these commentaries.

Another important consideration when determining how these results should be interpreted with respect to clinical practice is how the nature of samples compared in this study differ from the way silicone is used in the fabrication of facial prostheses. Many other factors affect the appearance of silicone in a facial prosthesis including the use of extrinsic and intrinsic glazes, the use of flocking, the form of the prosthesis, the presence of retentive elements embedded in the prosthesis, and the surrounding anatomy of the patient. All these factors alter the appearance of the silicone's color. It is also important to note that while this study compares differences between samples of silicone, the ultimate goal of determining thresholds of perceivable color difference lies in the production of silicone prostheses that are intended to match skin. Skin and silicone have very different properties; skin is multilayered and each of its layers reflect and absorb light differently.[20,21] Geometric attributes of an object's surface such as glossiness or the angle of illumination and observer can affect the viewer's perception of object color and result in geometric metamerism.[20] As such, the nature of spectral reflectance and therefore apparent color generated in each material under otherwise identical viewing conditions are not the same. It should be assumed that thresholds of perceivable color difference will be different when comparing silicone to silicone and when comparing silicone to skin. Observer metamerism due to differences in viewer color perception will also alter an individual's perception of color match.[20]

Given the current state of color matching technology it is not possible to rely entirely on these devices to produce realistically colored prostheses. Given the complexity and limitations of color measurement in silicone and skin, further research will be required before prostheses can be colored through this technology alone. Skin color is perpetually changing, the static color of silicone cannot match perfectly in all situations. However, establishing a benchmark for perceivable color difference in silicone, and using this to determine a clinical threshold of acceptability for color matching are important steps towards improving the application of this technology clinically and ultimately reducing the human variability involved in this aspect of facial prosthesis production. The results of this study should be taken as a step towards defining this threshold.

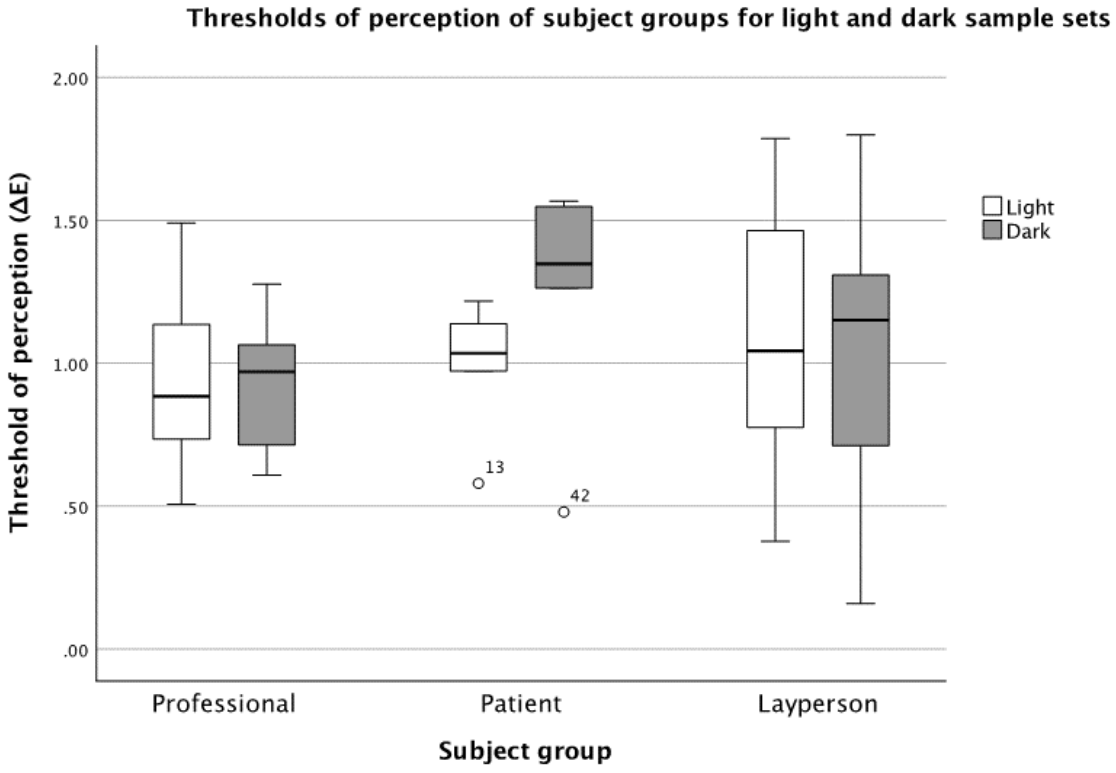

Fig 7. Boxplots showing the distribution of perception thresholds (ΔE) for light and dark sample sets for three groups of subjects.

CONCLUSION

The threshold of perceivable color difference in silicone was calculated to be approximately ΔE = 1.0, which was predicted. The study failed to find significant differences in thresholds among subject groups and between sample sets of different lightness. Predictions based on previous studies findings slightly lower thresholds in professionals who work with color than other subject groups, and in the lighter colored sample set than the darker set were not supported.

The findings of this study provide a valuable step towards better understanding and integrating technology in the production of silicone facial prostheses. Assessing and restoring the discoloration that accompanies prosthesis aging could also be aided by the use of this technology. A quantifiable measure of how color changes make a visible difference in prosthesis appearance may lead to a better understanding of how to prevent and correct these changes, as well as assisting in planning the timing of treatment and remaking prostheses. While more information is needed to definitively establish a clinical standard for acceptable color difference between silicone and patient skin, the findings of this study can be viewed as a step towards determining a standardized ΔE value that anaplastologists and related professionals can apply to computer-assisted color matching in the clinic. This will allow for greater consistency among clinics, higher quality prostheses, more efficient delivery of care, and a higher standard of care for patients. It also allows for research in the area of spectrophotometry and digital color formulation to be standardized and relevant comparisons to be made, which will allow for more consistent research to be conducted and further advances to be made in the field of anaplastology. Research in digital color matching allows for improved application of technology and ultimately more predictably colored prostheses with less metamerism. Possibilities for remote care are enhanced through the use of this technology. It also offers potential for reducing the time patients spend receiving treatment, contributing to improvement in overall patient satisfaction, and overall rehabilitation and treatment experience.

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